Advanced Topics in Science and Technology of Concrete

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Week - 01
Lecture - 01

Aggregates and their effects on concrete properties - Part 1

Greetings and welcome to this lecture on aggregates and their influence on concrete properties. This lecture is part of a SPARC project, which represents a collaboration between the civil engineering departments at the Indian Institute of Technology, the University of Cape Town in South Africa, and the university where I am based, which is the University of Witwatersrand in Johannesburg, South Africa. In this lecture, I intend to consider the nature of concrete aggregates and, more importantly, the aspects of concrete aggregates that influence the behaviour of concrete both in its wet or plastic state as well as in its hardened state. It is best to start with a broad classification of aggregates just to ensure that we understand what it is we are talking about. We consider aggregates as natural aggregates in the first instance, and that is by far the largest proportion of aggregates that is used in concrete around the world. This is obtained from natural geological rock sources that are reduced in size either by natural mechanical and weathering processes, for example, river gravels or sands, pit sands.

These are usually extracted directly from the ground and may well be sieved in order to improve size distribution or grading. Then, of course, we have natural aggregates that are mechanically crushed and sieved from larger fragments of parent rock. Usually, this is obtained by drilling and blasting of intact rock layers in a quarry. We then also have manufactured aggregates. This is usually lightweight or high-density aggregates manufactured for particular forms of performance in concrete. And it is usually obtained by thermal processing of natural materials, for example, expanded shale or iron ore fragments. We then also have recycled aggregates, which is really the subject of this course, and this is obtained by crushing and grading of suitable materials such as concrete and masonry rubble, as well as particular types of glass and plastic waste that are used in concrete. Just important distinction: we distinguish between coarse aggregate, which are fragments that are larger than 5 mm in size, and fine aggregate in concrete, which are fragments smaller than 5 mm in size.

Let's start by considering the influence of aggregates in concrete. Now of course, anybody who has worked with concrete will know that aggregates make up about 75–80% of the mass of concrete mixture, and as a result, they have a profound influence on the fresh and hardened properties of concrete. There was a time when aggregates were thought of as an inert filler in concrete, and of course this is not true, and we fully understand that aggregates are more than materials that is meant to reduce the volume of cement paste and, as a result, reduce the cost of the concrete. Well, of course it does that; its influence is a lot more than simply an inert filler. A few of the important properties of aggregates that influence concrete behaviour. Firstly, the maximum size and distribution of grading or of particle sizes.

The particle shape and its surface texture. The geological origin, mineralogy, and crystallography of the aggregate that is being used. The density, strength, and elastic modulus of the aggregate itself. And then the water absorption properties of the aggregate. And as I go through this lecture, we will cover and consider all of these aspects as we go along. And of course, the first point to start is to consider the effects of aggregate on concrete mixture design. When we do start out with the process of mixing, designing the mixture of concrete, we have to consider the nature and characteristics of the aggregate that are to be used. So the first principle is that good concrete mixture design aims to maximize the proportion of aggregate while at the same time providing suitable workability of the concrete. That is a little bit of an art in achieving the right balance. And the reason we do that is we want to reduce the cost, we want to reduce thermal movements, we want to increase abrasion resistance, we want lower elastic and time-dependent deformations, improve durability in particular environments of the concrete.

Aggregate size and distribution influence the available surface area that is to be coated by cement paste. And this is an important consideration because it influences the water demand for a given workability of concrete. Aggregate shape and surface texture influence the inter-particle friction during mixing and placing of concrete, and this influences the volume of the paste, that is, the cement and water that is necessary for a given workability. Flaky aggregate particles, rough surface texture, small particles, and poor particle size distribution will all cause an increase in the volume of cement paste in concrete. And this, of course, is for a given workability and strength requirement.

Competent and durable concrete demands careful attention to aggregate characteristics, without which we will be in trouble to ensure that we produce suitable concrete for structures. These tables give some indication of the effects of aggregate on water requirements in concrete, and here I've shown you on the left-hand side, the table shows the water requirements for different cementitious materials in relation to the presence of aggregate and the quality of that aggregate. So this is indicative values; they are not absolute. If you had to make cement paste of a particular workability, you would need about 500 litres to produce a cubic metre of medium-workability cement paste. If you added sand to that mixture, a poor sand, you would need about 400 litres, and you could continuously increase or rather decrease the amount of water required to produce a given workability simply by increasing the size of the aggregate and, of course, ensuring its distribution through option or opting for a fairly good sand.

And what this table also shows is that if you have a good sand and use a 37-mm stone size, you would get down to 160 litres of water to produce a cubic metre of material. On the right-hand side, the table shows the effect of large aggregate sizes on water requirement of concrete, and as you can see, if we start with a baseline of 19 mm of aggregate, as you increase the large aggregate size, you can reduce the water content, and this is really an effect of surface area. Larger aggregates have smaller surface area, and in general, you can reduce the water requirement to produce a given workability quite significantly by using a larger aggregate. Of course, if you use a smaller, coarse aggregate, you end up having to add water to maintain your workability. A comment of course on the large aggregate size is that increasing aggregate size is limited by things like the spacing of reinforcement, and 150 mm aggregate size is usually only limited to mass concrete structures such as dams or very large foundations where you don't have too much reinforcement or where there is reinforcement, the spacing between bars is quite large.

But I think this slide gives you a very good sense of the effects of aggregate size and sand quality on water demand. Of course, you will understand that the reason we are so concerned with water demand is because, as we increase water content, we also have to increase cement content in order to maintain the water-to-cement ratio and, so maintain the strength requirement of the concrete. Less water, therefore, means less cement for the same water-to-cement ratio. Just a comment about the role of coarse aggregate in concrete. Coarse aggregates are usually in a fairly narrow size range. Aggregates that are nominally indicated as 19 mm usually has particles in the range from about 17 to 25 mm, and this will produce what we call a gap-graded profile when mixed with concrete sand. In other words, there are really no sizes between 5 mm and 17 mm. Sometimes manufacturers produce a more continuously graded stone size ranging from 9 to 25 mm, and this is also sold nominally as a 19 mm aggregate. This is perfectly acceptable, but does require one to adjust the amount of sand in the mixture. For crushed rock aggregates, particle shape is strongly influenced by the type of crusher that is used in the crushing process.

And if a manufacturer has the wherewithal and availability, it does offer good opportunity for modifying particle shape simply by changing the type of crusher that is used to crush the material. Just to look at some examples of coarse aggregates in concrete, here is an example of a very large mass concrete element that used large river pebbles, in this case up to 80 mm in size, as the coarse aggregate. What is interesting is that these are river pebbles; they are fairly rounded, have a good particle shape, and will make a good concrete as well. On the other hand, here is a nominally 19-mm aggregate which is rather angular and flaky. It's an iron-rich quartzite available here in South Africa.

What is interesting is the very flaky nature of this material, which will cause particle interaction friction and may in fact have the effect of reducing workability. Look how acute some of the angles are on these particles. Here is an example of a rounded to angular coarse aggregate particle. It happens to be a mixture of shale, which is the dark areas, the dark grey to black aggregate particles, in a mixture with quartzite, which are the lighter coloured particles. And again, the particle shape is a lot more pleasant than the earlier flaky quartzite that I showed you. Here, the corners are a lot more rounded. Here is an example of a fairly well-graded coarse aggregate, also sold as a 19-mm aggregate. In this case, it is a crushed granite. And particle sizes range from about 20 mm to 25 mm down to 9 mm. But note, however, the fairly angular nature of the larger aggregate particles.

This is just, I am going to show you a few examples of texture. Here, I am trying to illustrate the effects of surface texture. On the left are fairly large crystal sizes in granite aggregate. The aggregate shape is chunky, with some flaky particles, particularly in the smaller sizes. On the right-hand side is a very fine-grained, glassy surface of quartzite aggregate.

More angular in its particle shape, sometimes a little bit flaky. But also a fairly friendly aggregate in the sense of the surface texture is quite smooth and will allow for less inter-particle friction when you are mixing and placing the concrete. Here are three examples, starting on the left, of a good particle shape but with a fairly rough surface texture of dolerite aggregate. Chunky to angular shape of a hornfels aggregate. And on the right, a good illustration of the effects of mineralogy on the composition of, in this case, limestone aggregate.

The two fairly very light-coloured particles are almost pure limestone. They end up being crushed as rounded and chunky particles. The other particles are also limestone but contain various degrees of other materials. As a result of the presence of these other crystal structures, the fracture planes are different, and so you end up with a more angular, more flaky particle shape all in the same batch of aggregate that is provided by the supplier. Just a sense of the acceptable grading limits for coarse aggregates.

And here I am showing a comparison between the British standards and the South African national standard. And I am sure there is an equivalent Indian standard. Most national standards will cover this sort of grading requirement. And it gives a good, and I really just don't want to go through the slide, but really provide you here as a reference to give you a sense of the limits of grading for what is coarse aggregate sizes. Nominally identified as a 38 mm aggregate, 19 mm, 12.5 mm and a 9.5 mm aggregate. But that would give you a sense of the range of acceptable particle sizes. Let's turn now to fine aggregate and think of the sand fraction of aggregate in concrete. Fine aggregates have a very, very large effect on the plastic properties of concrete. And this is mainly because of the much higher surface area of the particles that have been broken down, as we said, from 5 mm sizes down to very fine particle sizes of the sort of submicron sizes. Sand grading influences cohesiveness, bleeding, segregation, and surface finish of the plastic concrete.

And here I am referring to the ability for the concrete to remain coherent and cohesive when it is moved. A good example is when someone takes a spade full of concrete and then throws it at a distance to another place. Usually, the larger aggregate particles will segregate from the finer, more mortar fraction. And that refers to the cohesiveness of the material. Bleeding is a phenomenon where the lightest component of concrete, which of course is the water, rises to the surface because the heavier cement and aggregate particles are settling.

This causes water to rise to the surface, and if the bleeding is excessive, you will actually see pools of water forming on the surface of the concrete that has been freshly cast, compacted, and surface treated. Compaction relates to the ability; again is related to cohesiveness and will sort of affect or influence the way in which particles stay together or separate during compaction and segregate out. If the particle aggregate grading is not suitable during compaction, you will find that a lot of the heavier stone-sized particles will segregate and settle to the bottom. And that would be an issue related to aggregate properties but also to workability. The ability to finish the surface depends on the nature of the aggregates, particularly the sand.

And this is important in areas like parking surfaces, concrete pedestrian surfaces, insufficient sand or poor quality of sand will give you a very poor surface finish of the concrete. Workability is most strongly affected by the proportion of fine particles, particularly the minus 300 micron-sized particles. Again, this is effective of surface area. Fine aggregate with a high water absorption, if used in a dry state after mixing, will remove water from the mixture. So reduce the water-to-cement ratio and also reduce the workability of the plastic concrete.

So do pay attention to water absorption, and I will make reference to this a little later in talking about the hardened properties of concrete. Measures of the average particle size, depending on what the standards refer to, mostly people speak about the finest modulus of the sand. This, together with an understanding of the full grading profile of the sand particles, are very useful indicators of the suitability of sand in concrete mixtures. And a mix designer would do well to pay attention and become familiar with the influences of different forms of grading and different finest properties of aggregates, particularly sand aggregates.

Let's consider some examples now. Consider three examples of naturally weathered concrete sands. On the left, there is a fairly good particle shape of river sand with a low amount of coarse particles. In the centre, we see an almost single-sized river sand. This would probably have been deposited in a water environment which has a natural grading separation effect. This would mainly be used as a filler sand for a more coarse sand or coarse aggregate.

On the right, I show a fairly good particle shape of a naturally weathered pit sand, with particle sizes ranging quite well from fairly large particles to quite fine particles. That would probably make a very good concrete sand. Let's look at some crushed sand from parent rock. On the left is a quartzite-crushed sand with quite angular and flaky particles and certainly an excessive amount of fine aggregate particles. In the centre is an angular and platey shape of a crushed dolomite with insufficient fine material, and this is an example of a sand that would definitely need a fine filler sand in order to give it a better distribution on the fine end of the grading curve.

On the right is a fairly well-graded sample of crushed granite sand, and again, you see good particle sizes, with large particles grading right down to very fine aggregate particles. Here, I just wanted to give you a sense of the grading limits for aggregate sands. These would be the grading limits in the South African recommendations for concrete sands, and these set the upper and lower limits of grading for concrete sands to be used in South Africa. Let me emphasise that it is possible to make competent concrete if your grading does not exactly conform to these profiles. However, that will require a little bit of sophisticated approach to mix design and perhaps judicious use of admixtures, but it is possible to make competent concrete even if the sand doesn't adhere to these upper and lower grading limits.

So by all means, do test the sand; there is no reason to discard particles or certain fractions of the sand simply because it doesn't fit in the recommended grading limits. These grading limits are meant to be a guide and will usually give you a good aggregate sand for concrete if it lies within these limits.